THE PHYSICAL CHEMISTRY OF THE CRYSTALLIZATION AND MAGMATIC DIFFERENTIATION OF IGNEOUS ROCKS

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II

$CaMgSi_2O_6$ (DIOPSIDE) AND SiO_2

The binary eutectic between $CaMgSi_2O_6$ (melting-point = 1391°) and SiO_2 (melting-point = *ca.* 1700°, see p. 330) consists, according to Bowen (*Amer. Jour. Sci.*, Vol. XXXVIII [1914]) of 84 per cent Diops: 16 per cent SiO_2, with melting-point = 1362°, and at this temperature SiO_2 forms tridymite.

THE TERNARY SYSTEM $CaMgSi_2O_6$:Ab:An AND THE SEQUENCE OF CRYSTALLIZATION BETWEEN THE PYROXENE MINERALS AND PLAGIOCLASE

The ternary system between the chemically pure substances $CaMgSi_2O_6$, $NaAlSi_3O_8$, and $CaAl_2Si_2O_8$ has recently been explained by N. L. Bowen in a treatise "The Crystallization of Haplobasaltic, Haplodioritic, and Related Magmas" (*Amer. Jour. Sci.*, Vol. XL [1915]).

The melting-points are: $CaMgSi_2O_6$, diopside = 1391.5°. $CaAl_2Si_2O_8$, An = 1550 ± 2°. $NaAlSi_3O_8$, Ab = 1100 ± 10°.

The binary eutectic Diops: An was determined as 58 per cent Diops: 42 per cent An, with melting-point at 1270°.

On account of the extremely high viscosity of the melting masses, consisting of predominant Ab, the binary eutectic between Diops and Ab could not be determined, but by extrapolation (see Fig. 6) it lies at only a few per cent of Diops to nearly 100 per cent Ab, and naturally at a temperature lower than the melting-point of Ab, consequently somewhat lower than 1100°, thus a couple of hundred degrees lower than the eutectic between Diops and An. From the theoretical explanation of Schreinemaker

it appears (cf. p. 337) that the ternary system Diops:Ab:An must form two melting-planes, one for Diops and the other for Ab+An. This is verified by Bowen's experimental investigations, whereby further is proved that the eutectic line between

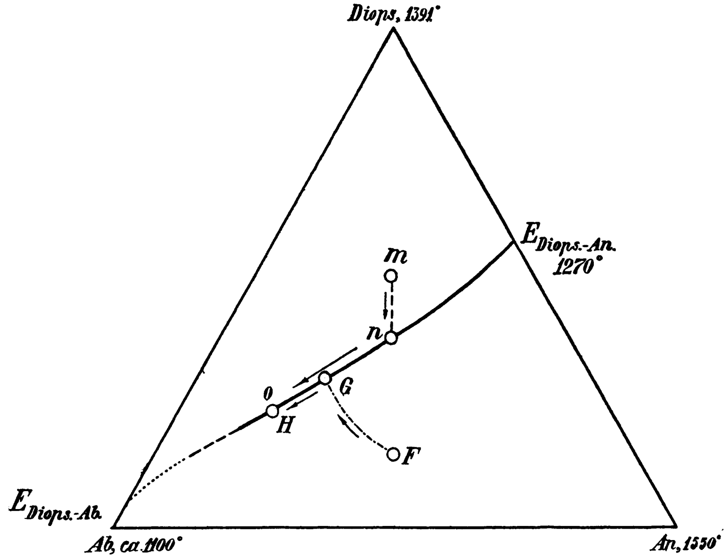

FIG. 6.—The ternary system An:Ab:Diops (horizontal projection), after Bowen

$E_{Diops.-An.}$ and $E_{Diops.-Ab.}$ has a *continuous* decline, without a maximum or a minimum. From Bowen's diagram (Fig. 6) I calculated some points on the eutectic line.

			Melting-Points
58 Diops:42 An: 0 Ab	or	58 Diops:42 $An_{100}Ab_0$	1270°
51 Diops:39 An:10 Ab	or	51 Diops:49 $An_{80}Ab_{20}$	*ca.* 1260°
44 Diops:36 An:20 Ab	or	44 Diops:56 $An_{65}Ab_{35}$	*ca.* 1238°
38 Diops:32 An:30 Ab	or	38 Diops:62 $An_{50}Ab_{50}$	*ca.* 1235°
33 Diops:27 An:40 Ab	or	33 Diops:67 $An_{40}Ab_{60}$	*ca.* 1225°
28 Diops:22 An:50 Ab	or	28 Diops:72 $An_{30}Ab_{70}$	*ca.* 1215°
23 Diops:17 An:60 Ab	or	23 Diops:77 $An_{22}Ab_{78}$	*ca.* 1205°
18 Diops:12 An:70 Ab	or	18 Diops:82 $An_{15}Ab_{85}$	*ca.* 1185°

The sequence of crystallization is illustrated by some examples taken from Bowen's treatise, to which, however, I add a few comments. In a melt (*m*) of 50 per cent $CaMgSi_2O_6$ and 50 per cent $Ab_{50}An_{50}$—accordingly with a surplus of $CaMgSi_2O_6$—diopside

commences to crystallize, if subcooling is left out of consideration, at a temperature of 1275°. After the separation of a certain amount of diopside the melting mass arrives at a point (*n*, *ca.* 38 per cent Diops:62 per cent $Ab_{50}An_{50}$ and at a temperature of 1235°) on the eutectic boundary curve. Then a simultaneous crystallization of diopside and plagioclase commences, the latter in the beginning with a composition $Ab_{20}An_{80}$, but on continued cooling with continually less An. On the presumption of a *complete equilibrium* between the solid and liquid phases, accordingly between the already crystallized plagioclase and Ab+An in the solution, the composition of the crystallized plagioclase is continuously displaced. The quantity of the liquid grows continually less by continuous crystallization. The last remnant of liquid is spent at a point (*O* on Fig. 6) 23 Diops:60 Ab:17 An, at the melting-point 1200° and with a separation of a minimal quantity of plagioclase $Ab_{50}An_{50}$.

If, on the other hand, we choose a melt of 15 per cent $CaMgSi_2O_6$ and 85 per cent $Ab_{50}An_{50}$—consequently with a surplus of Ab+An—plagioclase of the composition $Ab_{20}An_{80}$ commences crystallizing at the temperature 1375° (see point *F* on Fig. 6). On continuous cooling at first only plagioclase crystallizes. On the presumption of a *complete equilibrium* the composition of the already separated plagioclase is continuously changed. In this manner a plagioclase Ab_1An_2 appears at 1300°. The eutectic boundary curve is reached at *G*, at a temperature of 1216°. Now a simultaneous crystallization of diopside and plagioclase commences, as the Ab:An relation in the separated plagioclase little by little is displaced. At 1200° the last remnant of liquid is spent, the entire mass of plagioclase having the composition $Ab_{50}An_{50}$.

With *lacking equilibrium* the first separated plagioclase remains unchanged. By the continuous separation of relatively An-rich plagioclase, the quantity of Ab in the solution increases continually, and even more strongly than by the equilibrium. In this manner, by the simultaneous crystallization of diopside and plagioclase along the eutectic boundary-line we here at last obtain a plagioclase with a very high percentage of Ab.

Bowen emphasizes—and rightly—that in a ternary system Ab:An:Diops (as in the analogous system Ab:An:Qu) there is

no eutectic *point*. But an eutectic *boundary curve* exists with *simultaneous* crystallization of plagioclase and diopside. This simultaneous crystallization does, however, not take place at a constant temperature, but continues some distance at decreasing temperatures. With complete equilibrium this drop of temperature is, however, relatively small, as by the examples above chosen: for 50 per cent Diops: 50 per cent Ab_1An_1, from 1235 to 1200°, and for 15 per cent Diops: 85 per cent Ab_1An_1 from 1216 to 1200°.

In deep-seated igneous rocks (with very slow solidification) a complete, or in special cases not quite but only approximately complete, equilibrium takes place between the solid and liquid phases (see a separate chapter in the following). And even in the more quickly cooled effusive rocks no completely lacking equilibrium appears, but an imperfect equilibrium, where the degree of imperfection is of a somewhat changeable nature.

With regard to the relations of crystallization, especially in the deep-seated igneous rocks, it is of subordinate importance whether the *simultaneous* crystallization of the final components takes place at a constant temperature (*eutectic point*) or—by a small displacement of the quantitative proportion between the components—within a small interval of temperature for a short distance along a *eutectic boundary curve*. Bowen disputes the justification of the term "gabbroidic eutectic" which I have previously used. I find, however, supported by Bowen's experimental investigations, that this term must be maintained, when we emphasize the fact that here we have to do with a short distance on a curve and not with a point.

We shall now examine the crystallization of the pyroxene minerals and plagioclase, especially in gabbros and norites, and shall commence with the well-known orbicular norite (orbicular quartz-norite) at Romsaas, in the Archaen formation, 50 km. southeast of Kristiania, described by several earlier investigators, especially C. Bugge.[1]

Romsaas, which is a small hill rising about 60 m. above the surrounding gneiss, consists chiefly of quartz-norite, with which

[1] *Kristiania Vidensk. Selskab*, 1906. Here the earlier works of L. Meinich (1878), Th. Hiortdahl (1878), and K. v. Chrustschoff (1897) are cited.

is connected another quite subordinate variety of norite (see the analysis in the chapter on norite in Part II). The entire

MINERALS AND ROCKS FROM ROMSAAS

Percentage of	Hypersthene	Biotite	Plagioclase			Orbicule	Intervening Mass	Orbicular Norite		Common Norite (with Pyrites)
								Calculated	Analyzed	
No.	41	42	43*a*	43*b*	43*c*	44	45	46	47	48
SiO_2	53.3	37.64	52.33	56.25	57.15	51.55	61.28	54.4	52.75	52.86
TiO_2	......	1.57	......	......	......	0.58	0.40	0.5	1.19 }	9.22
Al_2O_3	3.0	20.15	29.99	27.93	27.20	4.45	21.58	9.6	10.29 }	
Fe_2O_3	1.2 }	9.83	0.51	0.45	0.32	0.50	0.22	0.4	0.35	(0.47)
FeO	16.5 }		......	......	......	14.50	1.59	10.6	11.92	11.81
MnO	0.3	0.49	......	......	......	0.50	0.20	0.4	0.46	......
MgO	23.7	16.44	0.97	0.19	0.14	22.08	1.85	16.0	15.61	17.15
CaO	2.0	0.70	11.64	9.59	9.08	2.61	7.51	4.1	4.21	4.58
Na_2O	......	2.57	4.80	5.49	6.01	0.64	4.44	1.7	1.66	1.23
K_2O	......	7.01	0.42	0.16	0.26	0.56	0.74	0.65	0.81	1.03
P_2O_5	......	1.23	......	......	......	0.11	0.52	0.23	0.40	0.53
Ign.	......	1.70	......	0.22	0.27	1.28	0.40	1.0	0.92	0.99
Total	100.0	99.93	100.66	100.28	100.43	99.36	100.77	99.6	100.57	99.87

EXPLANATION

No. 41: Hypersthene (somewhat changed to hornblende) from the orbs, the medium of four well-conformable analyses, by Hiortdahl (2), Meinich, and Chrustschoff.—No. 42: Biotite from the orbicules by Bugge.—No. 43*a-c:* Different analyses of plagioclase from the intervening mass between the orbs, No. *a* (from the kernel of the plagioclase) by Meinich, Nos. *b*, *c* (from the exterior parts of the plagioclase) by Chrustschoff.—No. 44, the orb, and No. 45, the intervening mass between the orbs, by Bugge.—No. 46, the coarse-grained orbicular norite, calculated by myself, and originating from 70 per cent orbs (No. 44) and 30 per cent intervening mass (No. 45).—No. 47 orbicular norite with smaller orbs, analyzed by Bugge.—No. 48, the ordinary norite, analyzed by Bugge, whose analysis applies to a rock with 3.88 per cent pyrrhotite which I have deducted from the analysis, and recalculated to the sum found.

igneous field[1] has an area of only *ca.* 65,000 sq. m. In some places, in part directly at and in part quite close to the boundary of the norite field, the rock has an orbicular structure. We may

[1] See map and profile in Beyschlag, Kreusch, Vogt, *Erzlagerstätten*, I (2d ed., 1914), Fig. 191.

distinguish a variety (see Figs. 7 and 8) with large orbs of a diameter from about 4 to 8 or 9, mostly about 5 cm., and another variety with small orbs, of a diameter of about 2 cm. These orbs consist in the interior exclusively of hypersthene (0.28 $FeSiO_3$:0.72 $MgSiO_3$, if we leave out of consideration the links containing CaO and

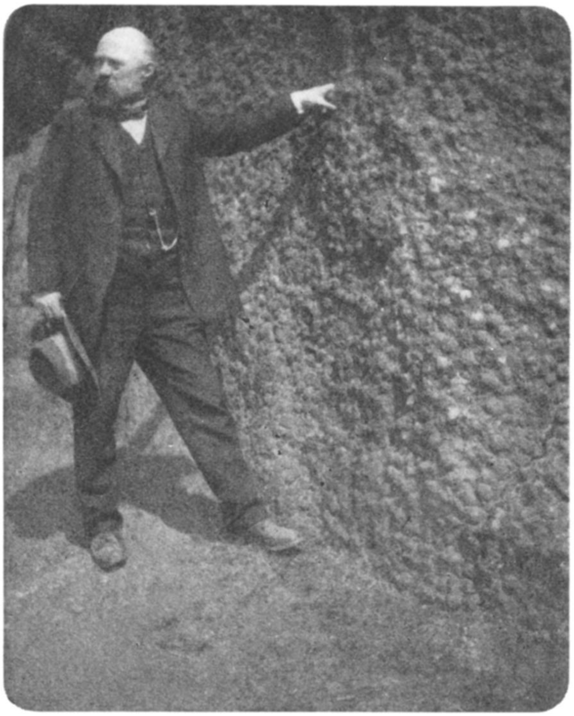

FIG. 7.—Orbicular quartz-norite from Romsaas, Norway

Al_2O_3) which, however, has been changed in part to hornblende. In the exterior part appears also some biotite which partly lies as shells or scales on the outside of the orbs (see Fig. 8). According to the detailed calculation which I effected on the spot, the rock with the large orbs consists (according to weight) of 70 per cent of orb substance (analysis No. 44) and 30 per cent of intervening mass (analysis No. 45). On this basis, the composition, No. 46, of the entire rock is calculated by myself. The close conformity

between analyses Nos. 46–48 prove that the orbicular rock, Nos. 46 and 47, is only a facies near the boundary of the ordinary quartz-norite (No. 48).

The mineralogical composition of the orbs (with some biotite in the exterior part) of the intervening mass (by Bugge), and of the entire quartz-norite (from my own calculation) are as follows:

	Orb	Intervening Mass	Total Quartz-Norite
Hypersthene	92.0	0	63.0
Biotite	7.2	10.0	8.0
Plagioclase	tr.	73.5	23.8
Quartz	....	15.0	4.0
Rutile	0.55	0.39	0.5
Apatite	0.23	1.18	0.9
Total	100.0	100.0	100.0

In addition there sometimes appear in the intervening mass small individuals of garnet, exceptionally also of pyrrhotite ("nickel pyrrhotite") in very small quantity.

The plagioclase of the intervening mass, which on the average may be placed at 47 Ab:3 Or:50 An, therefore almost exactly Ab_1An_1 varies between $Ab_{42}An_{58}$ (with a little Or, analysis No. 43*a*, with extinction 7°15′ on 001 according to Bugge) in the kernel of the individuals and $Ab_{55}An_{45}$ (analysis No. 43*c*, with extinction 3°30′) in the exterior zone. Locally the plagioclase contains still more Ab, according to Bugge with extinction on 001 of 1°15′, corresponding to about $Ab_{62}An_{38}$ (in both cases with a little Or). Concerning this matter we refer to some remarks in a following chapter.

Naturally the orbs are first formed, and only later the intervening mass solidified. Near the center of the orbs, the hypersthene individuals are to a great extent radially arranged. In the exterior part of the orbs[1] we find, on the other hand, an indication of concentric structure (see Fig. 8).

If we leave apatite and rutile out of consideration, we may distinguish between the following stages of crystallization (Fig. 9):

[1] Some inclusions of the material of the intervening mass also appear here and there in the orbs (cf. p. 320).

(1) hypersthene in great quantity (stage i); (2) biotite, in the exterior part of the orbs simultaneously with the crystallization of the rest of the hypersthene (stage ii), then followed some biotite alone, as scales or thin shells on the outside of the orbs (stage iii);

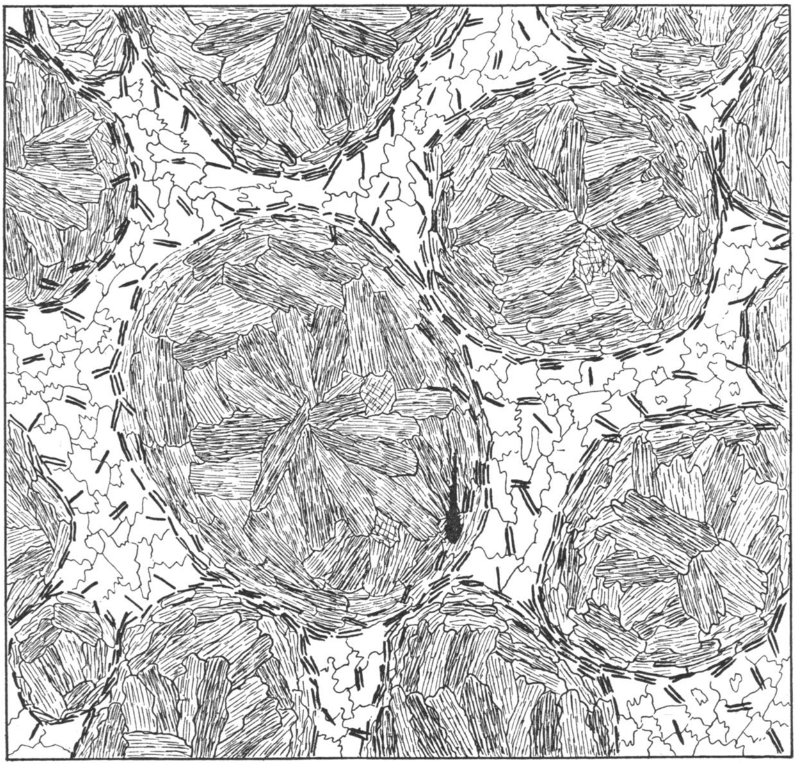

FIG. 8.—Section through the orbicular quartz-norite from Romsaas, Norway. Natural size. Lightly shaded mineral is hypersthene, dark is biotite, and white is feldspar and quartz.

(3) after the orbs were formed, the intervening mass had the composition of a biotite-quartz-diorite (analysis No. 45), and the crystallization became that usual in these rocks, viz., at first biotite (the close of stage iii), then plagioclase (stage iv), and finally also quartz (stage v) solidified.

We especially call attention to the following: In the magma, so extraordinarily rich in ferromagnesian metasilicate, *only hypersthene* crystallized at the beginning. Then the formation of this mineral stopped, as the ferromagnesian silicate still remaining in the magma entered into *biotite*. The change from hypersthene to biotite was probably caused by the quantity of H_2O present in the magma, and this quantity had been relatively enriched by the separation of the large quantity of hypersthene. We shall return to this matter in a following chapter.

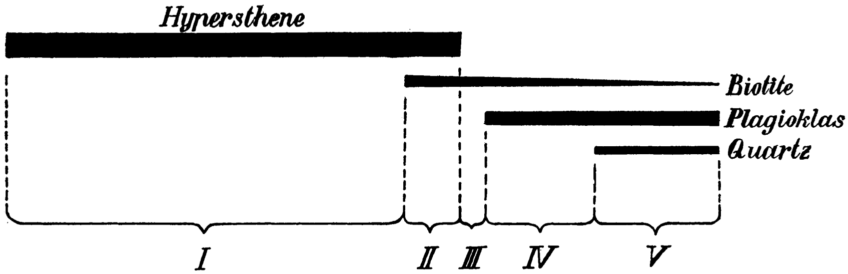

FIG. 9.—Diagram illustrating the different stages of the crystallization of the orbicular quartz-norite from Romsaas.

We further emphasize that from the original magma, so rich in ferromagnesian metasilicate, a quartz-dioritic magma was separated at a far-advanced stage of the solidification and there resulted, by continuous solidification, at last even a magma for special "oligoclase (or andesine) granite dikes," consisting of biotite, andesine ($Ab_{68}An_{32}$), and quartz. We refer to a special chapter in Part II.

The normal quartz-norite (Fig. 10) from Romsaas, consisting of *ca.* 63 per cent hypersthene (included a little secondary hornblende), 8 per cent biotite, 24 per cent plagioclase (Ab_1An_1), 4 per cent quartz, and, in addition, a little apatite, rutile, and pyrrhotite, in part shows accumulation (together-swimming or synneusis structure) of hypersthene individuals which often have a well-developed idiomorphic contour on their boundary toward the plagioclase or quartz. The hypersthene, therefore, must have crystallized completely or in a great measure before the plagioclase and the quartz.

The biotite appears partly in the *exterior* portions of the hypersthene individuals, and partly—and chiefly—grown on to these. The hypersthene in several places shows idiomorphic contours also against the biotite, the latter must accordingly chiefly have been formed at a latter stage than the former. The labradorite

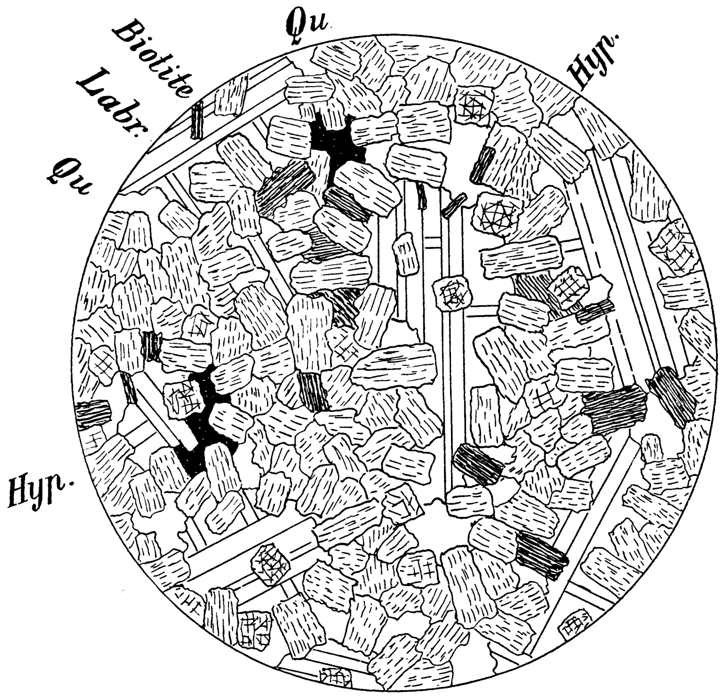

FIG. 10.—Quartz-norite from Romsaas. (Black = pyrrhotite)

and the quartz form an intervening mass between the accumulations of hypersthene, and accordingly crystallized at a somewhat later stage.

The investigation of the Romsaas rocks is in certain respects very instructive, but does not fully inform us of the relation of the crystallization between the hypersthene and the plagioclase, as the ferromagnesian silicate of the later stage entered into biotite instead of into hypersthene. We are therefore going to investigate some rocks where this phenomenon does not appear.

In the norites and gabbros, especially *rich* in orthorhombic or in monoclinic *pyroxene* (hypersthene-norites and diallage-gabbros) with relatively little, say 10, 20, or 25 per cent of labradorite, the pyroxene individuals to a very great extent show an idiomorphic contour against the plagioclase. Further, the pyroxene individuals are often to some extent accumulated in aggregates, consequently showing synneusis structure. On the other hand, the plagioclase shows no signs of idiomorphism but only appears as

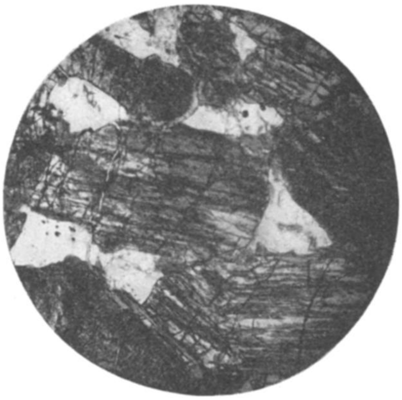

FIG. 11.—Photomicrograph (18:1)

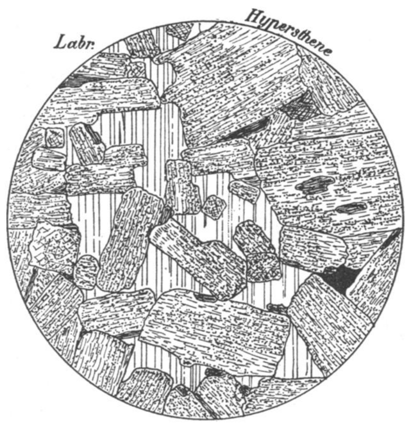

FIG. 12.—Drawing (11:1)

Norite from Meseel, Norway. Hypersthene with predominant idiomorphic outlines against the labradorite. The photograph represents the lower part of the drawing. The shaded mineral in small quantity is hornblende, the black pyrrhotite.

mesostasis (*Zwischenklemmungsmasse*) between the pyroxene individuals. This may be explained by the fact that an essential part of the orthorhombic or monocline pyroxene in question had solidified even before the commencement of the crystallization of the plagioclase. We must not draw the conclusion, however, that the pyroxene individuals in their entirety had crystallized at an earlier stage than the plagioclase. On the contrary, in some of the pyroxene individuals, we find the idiomorphic contour against the plagioclase lacking, and this must indicate a simultaneous crystallization of both minerals during the last stage of the solidification. As an example we refer to the photograph (enlarged 18:1) and

drawing (enlarged 11:1) of a hypersthene-norite from Messel (about 10 km. from Arendal, Norway), containing about 20 per cent labradorite (Ab_1An_1), nearly 80 per cent hypersthene (consisting, according to the determination of the optical character and of the

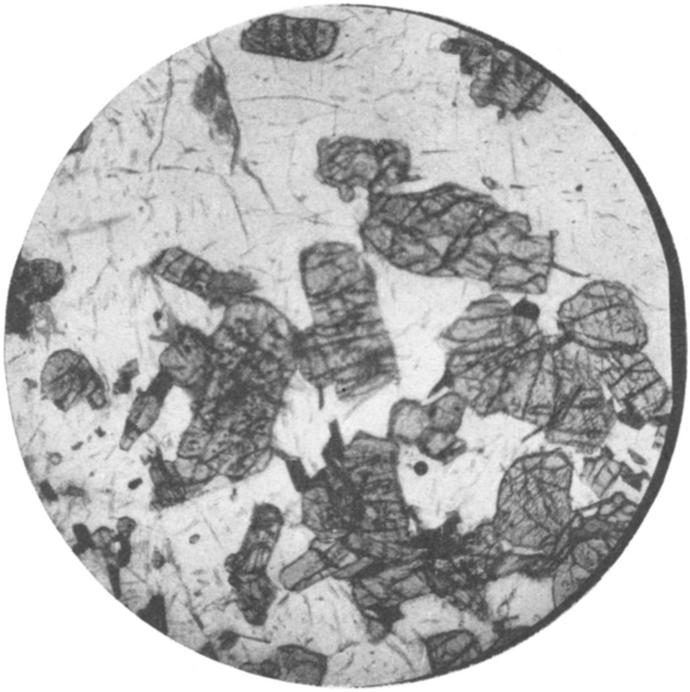

FIG. 13.—Norite from Skougen, Norway. The hypersthene, to a great extent, has idiomorphic outlines against the labradorite, and the hypersthene in several places shows synneusis structure. The biotite is inclosed in the exterior parts of the hypersthene individuals or is grown on these. (24:1.)

optic axial angle, of about 0.25 $FeSiO_3$:0.75 $MgSiO_3$), a little hornblende, and a little pyrrhotite, but no biotite, diallage, and oxidic iron ore.

In gabbros and norites, containing somewhat more plagioclase (labradorite), say 30, 35, 40, or 45 per cent, and correspondingly less pyroxene, we still find the pyroxene individuals to greater or lesser extent with idiomorphic contours against the plagioclase, while the latter lacks idiomorphism.

As an example we refer to Figures 20 and 21 and to Figure 13, microscopic photograph of a norite from Skougen in Bamle, Norway. This rock consists, according to microscopic investigations supported by chemical analysis (see Part II), of about 47 per cent hypersthene (according to the analysis of the

FIG. 14.—Anorthosite from Hitterö, Norway. The labradorite (Ab_1An_1, light) has idiomorphic contours against the hypersthene. (25:1.)

rock and the optical determination calculated as 0.32 $FeSiO_3$: 0.68 $MgSiO_3$), a trifle secondary hornblende, 48 per cent labradorite (*ca.* 38 Ab, 4 Or, 58 An, or about Ab_2An_3), 3 per cent biotite, and 1–2 per cent magnetite-ilmenite, see later (Figs. 31–32), 0.07 per cent apatite, and a little pyrite (0.24 per cent S).

On the other hand, in rocks especially *rich in plagioclase* we find throughout the idiomorphism more or less well developed by the plagioclase, but not by the pyroxene. This applies to all anorthosites which I have investigated, where the ferromagnesian

silicates, indifferently whether hypersthene (Fig. 14), diallage, or olivine (see Figs. 23 and 24), for an essential part form a mesostasis between the plagioclase (labradorite or sometimes bytownite).

The question in hand, I have to some extent considered in a paper, accompanied by several analyses, published in the *Quart. Jour. of the Geological Society*, 1909, on labradorite-norite with porphyritic labradorite crystals from Flakstadöen in Lofoten. Referring to the quantitative analysis of this rock, given in the chapter on anorthosite-norite in Part II, I shall here give a short résumé. The entire rock consists of:

ca. 70.65 per cent labradorite, 55 An, 39 Ab, 6 Or
ca. 6.3 per cent Fe_3O_4 } 7.2 per cent "titanomagnetite"
ca. 0.9 per cent $FeTiO_3$ }
ca. 10.0 per cent hypersthene
ca. 10.0 per cent diallage
ca. 2.3 per cent biotite
ca. 0.9 per cent apatite

Relatively to the entire rock, there first crystallized 23 per cent prophyritic labradorite of a composition 61 An, 33 Ab, 6 Or, and occurring as very large, up to 15–18 cm. long and 6–8 cm. wide, crystals, thick tabular along (010). The remainder, 77 per cent, form a coarse-grained groundmass, consisting of:

ca. 61.9 per cent labradorite, 52 An, 42 Ab, 6 Or
ca. 8.1 per cent Fe_3O_4 } 9 per cent "titanomagnetite"
ca. 0.9 per cent $FeTiO_3$ }
ca. 13.0 per cent hypersthene
ca. 13.0 per cent diallage
ca. 3.0 per cent biotite
ca. 0.12 per cent apatite

In this groundmass the labradorite continued crystallizing, and some magnetite (or "titanomagnetite") commenced to form, of which more below. Only at a somewhat later stage, after the quantity of hypersthene and diallage had risen somewhat above 30 per cent, the pyroxene commenced forming.

The *hyperitic* (or ophitic) texture of plagioclase crystals, with tabular development along (010), appears in the gabbro rocks only when the latter contain at least about 55 per cent plagioclase (labradorite). The laths of plagioclase show partial idiomorphism

against the hypersthene (see, for example, Figs. 15 and 16) or the diallage, which ordinarily entirely lack idiomorphism. We may consequently draw the conclusion that the crystallization of labradorite in these plagioclase-rich rocks must have commenced before the beginning of the solidification of the pyroxene. The idiomorphism of the labradorite, however, is often only quite slightly developed, as illustrated in Figures 15 and 16. This tells us that

FIG. 15.—Photomicrographic (19:1)

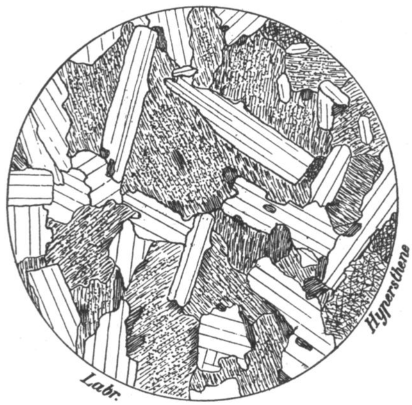

FIG. 16.—Drawing (35:1)

Hyperitic- (or ophitic-) structured norite from Erteli, Norway. Consists of about 56 per cent labradorite (*ca.* Ab_3An_7), 41 per cent hypersthene (0.31 $FeSiO_3$: 0.69 Mg SiO_3), a little magnetite and pyrrhotite (0.07 per cent S, see Fig. 46), 0.09 per cent apatite; see analysis in Part II. The drawing (35:1) represents the central and lower parts of the photograph (19:1).

only a certain small part of the labradorite, in this case, had solidified before the pyroxene began forming.

Rosenbusch[1] emphasized, and rightly, with regard to the gabbros, that in rocks *rich in plagioclase*, the plagioclase, and in the varieties *rich in diallage*, the diallage, develops in idiomorphic individuals, and further, that in rocks rich in diallage, the idiomorphism of the diallage is the more prominent the greater its quantity. "Man wird also scheinbar genötigt ein gewisses Schwanken in der Reihenfolge der Ausscheidungen anzunehmen." But Rosenbusch did not engage in the physicochemical interpretation of the phenomenon.

[1] *Mikroskop. Phys. d. Mass. Gest.* (4th ed., 1907), II, 1, p. 364.

According to my own extensive investigations of the question in hand (whereof I have only given a very short résumé) the facts previously set forth by Rosenbusch are confirmed, and we draw the conclusion that *the sequence of crystallization of plagioclase and pyroxene depends upon the relative quantity* of the two minerals, for *the crystallization commences with the solidification of the mineral present in excess of a certain limit.*

I have bestowed much labor on the determination of this limit, trying to get it as exactly as possible, by structural investigation on a series of norites, and partly also of gabbros, of which we have numerous quantitative analyses, so that the proportion by weight between the plagioclase (with a determined Ab:An relation) and the pyroxene may be quite exactly calculated. We then find that the limit essentially depends on the composition of the plagioclase.

As an example may be mentioned that in a diallage-bearing quartz-norite with about 58 per cent SiO_2 (and standing on the boundary near quartz-hypersthene diorite), containing about 28 per cent pyroxene (hypersthene with a little diallage), about 60 per cent plagioclase (andesine, $Ab_{68}An_{40}$), a trifle orthoclase, about 4 per cent biotite, about 1 per cent iron ore, and about 5 per cent quartz, the hypersthene in a great measure appears with idiomorphic contour against the plagioclase (andesine). In rocks with basic labradorite, as Ab_1An_2, the plagioclase on the other hand partly shows an idiomorphic contour against the pyroxene, even when there is as much pyroxene as 35–40 per cent present. The individualization boundary, determined by the sequence of crystallization, amounts approximately in the deep-seated rocks to:

With $Ab_{30}An_{70}$ about	45–50 per cent pyroxene	
With $Ab_{40}An_{60}$ about	40–45 per cent pyroxene	
With $Ab_{50}An_{50}$ about	35–40 per cent pyroxene	the remainder plagioclase
With $Ab_{60}An_{40}$ about	25–30 per cent pyroxene	
With $Ab_{70}An_{30}$ probably	15–20 per cent pyroxene	

By pyroxene we here understand, with regard to the norites, hypersthene of the common composition of these rocks, viz., 0.3–0.35 $FeSiO_3$:0.7–0.65 $MgSiO_3$, and, with regard to the gabbros, diallage with about the corresponding iron content.

We are able to obtain a more detailed determination of the individualization boundary by studying a series of porphyritic rocks, with phenocrysts of plagioclase when this mineral is in excess, and of pyroxene when the ferromagnesian silicate is in excess. I am, however, far from having sufficient material for such a precision-determination.

Because of physicochemical considerations we must draw the conclusion that the *individualization boundary* here shown is a *eutectic* boundary between pyroxene and plagioclase. And our individualization boundary shows almost exactly the same course as the eutectic boundary curve between diopside and Ab+An, determined by Bowen at a pressure of one atmosphere.

If we imagine a quartary system, consisting of Ab, An, $CaMgSi_2O_6$ (Diops), and $CaFeSi_2O_6$ (Hed), this system will separate into two fields, each consisting of a continuous mix-crystal. Ab+An surely, and Diops+Hed almost certainly, belong to type I. The difference between this quartary system and the ternary system Ab+An:Diops (Fig. 6), or Ab+An:Qu (Fig. 5), is chiefly that for the melting-plane of the independent component in the ternary system (ex. Qu on Fig. 5) is substituted a melting-plane of a binary mix-crystal combination (Diops+Hed).

The eutectic boundary between basic plagioclase and hypersthene I term the "noritic," between basic plagioclase (labradorite, exceptionally bytownite) and monoclinic pyroxene (diallage) the "gabbroidic," and between somewhat more acid plagioclase (andesine, in some cases oligoclase) and the ferromagnesian constituent, the "dioritic" eutectic boundary. We shall calculate the composition of this boundary on the assumption that it has the following course with varying proportions of Ab and An:

45 per cent hypersthene (or diallage): 55 per cent $Ab_{20}An_{80}$
40 per cent hypersthene (or diallage): 60 per cent $Ab_{35}An_{65}$
35 per cent hypersthene (or diallage): 65 per cent $Ab_{50}An_{50}$
33 per cent Augite (or diallage): 67 per cent $Ab_{55}An_{45}$
27 per cent Augite (or diallage): 73 per cent $Ab_{60}An_{40}$
20 per cent Augite (or diallage): 80 per cent $Ab_{75}An_{25}$

For hypersthene we assume: 48 $MgSiO_3$, 30 $FeSiO_3$, 5 $MgAl_2SiO_6$, 4 $MgFe_2SiO_6$, 13 $CaFeSi_2O_6$ = 51.2 per cent SiO_2, 2.5 Al_2O_3, 2.5 Fe_2O_3, 2.9 CaO, 20.1 FeO, 20.8 MgO. And for the plagioclase respectively $An_{78}Ab_{18}Or_4$, $An_{62}Ab_{32}Or_6$, and $An_{47}Ab_{47}Or_6$.

	Noritic Eutectic Line between Plagioclase and Hypersthene		
	I	II	III
	45 Hyp: 55 $An_{78}Ab_{18}Or_4$	40 Hyp: 60 $An_{62}Ab_{32}Or_6$	35 Hyp: 65 $An_{47}Ab_{47}Or_6$
SiO_2	49.7	51.9	54.5
Al_2O_3	19.3	19.1	18.8
Fe_2O_3	1.1	1.0	0.9
{FeO	9.1	8.1	7.1
{MgO	9.3	8.3	7.3
CaO	9.9	8.7	7.1
Na_2O	1.2	2.3	3.6
K_2O	0.4	0.6	0.7

For the diallage of the gabbros we assume: 40 $CaMgSi_2O_6$, 36 $CaFeSi_2O_6$ 7 $MgAl_2SiO_6$, 11 $FeFe_2SiO_6$, 6 $MgSiO_3$ = 47.5 per cent SiO_2, 3.8 Al_2O_3, 6 Fe_2O_3, 13.1 FeO, 11.1 MgO, 18.5 CaO. And for the augite of the diorite: 52 $CaMgSi_2O_6$, 34 $CaFeSi_2O_6$, 3 $MgAl_2SiO_6$, 6Fe Fe_2SiO_6, 5 Mg SiO_3 = 50.45 per cent SiO_2, 1.65 Al_2O_3, 3.3 Fe_2O_3, 11.3 FeO, 12.2 MgO, 21.1 CaO.

	Gabbroidic Eutectic Line between Plagioclase and Diallage			Dioritic Eutectic Line between Plagioclase and Augite		
	I*b*	II*b*	III*b*	IV	V	VI
	45 Diallage: 55 $An_{78}Ab_{18}Or_4$	40 Diallage: 60 $An_{62}Ab_{32}Or_6$	35 Diallage: 65 $An_{47}Ab_{47}Or_6$	33 Augite: 67 $An_{42}Ab_{48}Or_{10}$	27 Augite: 73 $An_{32}Ab_{56}Or_{12}$	20 Augite: 80 $An_{22}Ab_{66}Or_{12}$
SiO_2	48.0	50.5	53.2	55.1	57.5	60.2
Al_2O_3	19.9	19.7	19.3	18.5	18.5	18.8
Fe_2O_3	2.7	2.4	2.1	1.1	1.0	0.7
FeO	5.9	5.2	4.6	3.7	3.0	2.3
MgO	5.0	4.4	3.9	4.0	3.3	2.4
CaO	16.9	14.9	12.6	12.6	10.4	7.8
Na_2O	1.2	3.3	3.6	3.8	4.8	6.2
K_2O	0.4	0.6	0.7	1.1	1.5	1.6

In the anchi-eutectic norites or gabbros with rather basic plagioclase (Ab_1An_2), the simultaneous crystallization of plagioclase and pyroxene will commence at about II (or II*b*) and be finished at about III (or III*b*), or at still less pyroxene and more of a relatively Ab-rich plagioclase, about equal to IV. And in the medium-basic anchi-eutectic diorites the simultaneous crystallization of plagioclase and pyroxene will commence about at IV (or between IV and V) and finish at about VI.

[*To be continued*]